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DOE/NV--1009

National Nuclear Security Administration

Subsurface Site Characterization Work Plan for the Rulison Site, Colorado

Controlled Copy No.: ___
Revision No.: 0

October 2004

Environmental Restoration
Division

U.S. Department of Energy
National Nuclear Security Administration
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SUBSURFACE SITE CHARACTERIZATION WORK PLAN FOR THE RULISON SITE, COLORADO

U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Las Vegas, Nevada

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**SUBSURFACE SITE CHARACTERIZATION WORK PLAN
FOR THE RULISON SITE, COLORADO**

Approved by: Signature Approved Date: 10/27/2004

Peter A. Sanders, Project Manager
Offsites Project

Approved by: Signature Approved Date: 10/27/2004

Robert M. Bangerter, Acting Division Director
Environmental Restoration Division

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List of Acronyms and Abbreviations

bgs	Below ground surface
COGCC	Colorado Oil and Gas Conservation Commission
DOE	U.S. Department of Energy
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DQO	Data Quality Objective
FEHM	Finite Element Heat and Mass (simulator)
ft	Foot (feet)
ft^3	Cubic foot (feet)
kt	Kiloton(s)
md	Millidarcy
SGZ	Surface Ground Zero
TOUGH2	Transport of Unsaturated Groundwater Heat (simulator)
USGS	U.S. Geological Survey

1.0 INTRODUCTION

Project Rulison was the second joint government-industry experiment to investigate stimulating and enhancing natural gas recovery from low permeability reservoirs by using nuclear explosives. The purpose of the Rulison test was to study the economic and technical feasibility of using underground nuclear explosions to stimulate production of natural gas from the low-productivity, gas-bearing Mesaverde Group in the Rulison Field. The experiment was conducted on September 10, 1969, and consisted of a 40-kiloton (kt) `nuclear explosive detonated at a depth of 8,426 feet (ft) (AEC, 1973). The detonation was followed by seven months of production testing.

The Rulison Site is located approximately 40 miles northeast of Grand Junction, in Garfield County, Colorado (Figure 1-1). The site underwent a general cleanup in 1972, when all equipment and materials not needed for future production testing were removed (AEC, 1973). After interest in further production waned, the remaining equipment at the site was removed, and the wells were plugged and abandoned in 1976 (ERDA, 1977). This effort included radiological sampling, decontamination, and site abandonment. In 1995, the U.S. Department of Energy Nevada Operations Office (DOE/NV) (now the DOE National Nuclear Security Administration Nevada Site Office) began voluntary remediation of a mud pit at the Rulison Site. Testing of the mud pit revealed trace amounts of diesel fuel, chromium, barium, and lead; however, no levels of radionuclides were detected above natural background. Corrective actions were performed (DOE/NV, 1996), and closure of the pit was approved by the State of Colorado in 1998 (Stoner, 1998). Although restoration of the land surface at the Rulison Site is now complete, closure of the subsurface has not been documented.

1.1 Purpose

The purpose of the subsurface investigation at the Rulison Site is to obtain the information needed to achieve a site closure that is protective of human health and the environment. The process follows the one developed for the Rio Blanco nuclear gas stimulation site, which was approved by the State of Colorado (DOE/NV, 2000a). For the Rulison subsurface, this entails evaluating if the existing subsurface intrusion boundary is adequately protective or needs to be modified. Existing information will be evaluated and possible contaminant movement away from the test cavity will be modeled to understand contaminant fate and transport. Depending on the outcome of the evaluation, a risk analysis may also be performed.

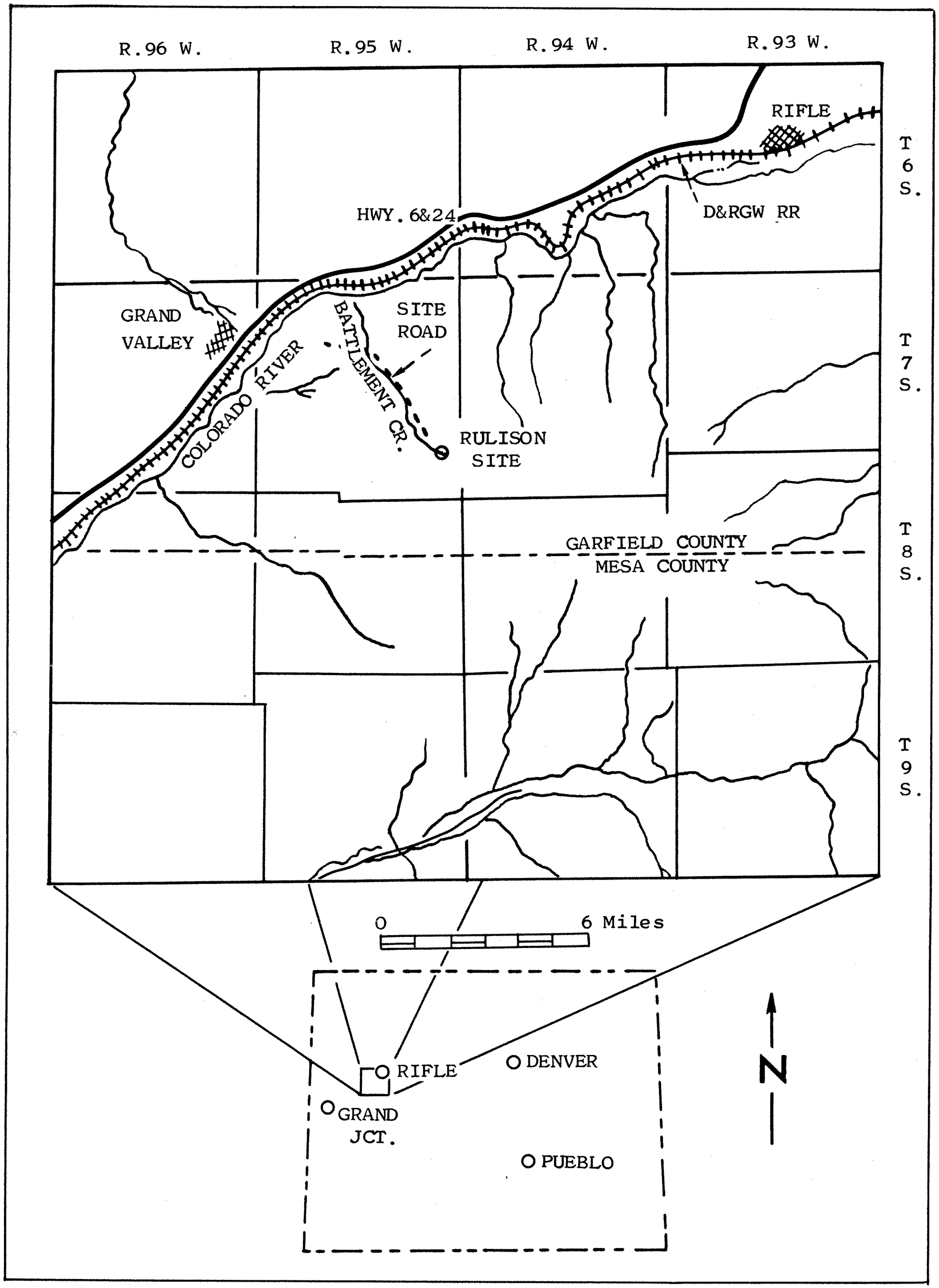


Figure 1-1
Location Map of the Rulison Site (Nork and Fenske, 1970)

1.2 Scope of Work

The following Data Quality Objectives (DQOs) define the work scope for the Rulison subsurface:

- Determine the nature and extent of contamination in the subsurface and how it changes with time
- Develop likely scenarios for future resource development and determine their impact on the extent of contamination
- Evaluate contaminant extent relative to the existing subsurface drilling restrictions

The subsurface work effort will rely on analysis of existing data and application of those data in numerical models of flow and transport. The focus will be on the deep subsurface around the test horizon in the Mesaverde Formation. The natural gas modeling effort will consist of locating and evaluating subsurface data, and identifying numerical models capable of handling the necessary physical processes. Once the numerical model of flow and transport under nonstressed conditions is developed, stressed conditions will be simulated. “Stressed” means that the impact of natural gas production will be simulated with the model by including hypothetical wells. Results will be evaluated to determine the adequacy of the existing subsurface restrictions and propose a modified exclusion boundary, if needed.

1.3 Investigation Work Plan Contents

This document provides a description of past and present subsurface site conditions, a description of the results of applying the DQO process to the site, and a description of the methods and procedures to be used for investigation activities. This work plan is organized as follows:

- Section 1.0 – Introduction
- Section 2.0 – Description of Site
- Section 3.0 – Data Quality Objectives
- Section 4.0 – Subsurface Modeling Work Plan
- Section 5.0 – Reporting
- Section 6.0 – References

Please refer to the *Underground Test Area Quality Assurance Project Plan, Nevada Test Site, Nevada, Revision 4* (NNSA/NSO, 2003) for information on quality assurance for the Rulison subsurface modeling project.

2.0 DESCRIPTION OF SITE

The following section provides a description of the Rulison Site.

2.1 Physical Setting

This section describes the location of the Rulison Site and the land status, environmental setting (including topography, vegetation, and surface water), and geologic setting.

2.1.1 Land Status

The land surface at the Rulison Site is privately owned. The deed between the landowner and the government allowing use of the land surface during the Rulison test has since been released. The subsurface operating rights, from the surface of the earth to a depth of 500 ft below the base of the Mesaverde Formation in Lot 11, NE ¼, SW ¼, of Section 25, Township 7 South, Range 95 West, 6th Principal Meridian, Garfield County, Colorado, were granted to the government by Austral Oil Company under the terms and conditions of the Rulison contract. At the conclusion of the project, the government retained a deed controlling drilling (described below) and the right to place a monument at surface ground zero (SGZ).

Two plugged wells exist at the site: the R-EX Well, used for exploration and post-stimulation testing, and the R-E Well, where the nuclear device was located. The emplacement well for the nuclear device was centered 1,976.31 ft east of the west line and 1,813.19 ft north of the south line of Section 25, Township 7 South, Range 95 West, 6th Principal Meridian (Figure 2-1). This corresponds to geodetic coordinates of longitude 107 degrees 56 minutes 53 seconds west and latitude 39 degrees 24 minutes 21 seconds north. Currently, intrusion into the subsurface is restricted below a depth of 6,000 ft within lot 11, NE quarter, SW quarter, of Section 25, Township 7 South, Range 95 West, 6th Principal Meridian, Garfield County, Colorado.

2.1.2 Environmental Setting

The Rulison Site is on the north slope of Battlement Mesa, in a mountain valley extending along the upper reaches of Battlement Creek. The site elevation is approximately 8,200 ft. The valley is open to the north-northwest and is surrounded on the other sides by steep mountain slopes rising above 9,600 ft.

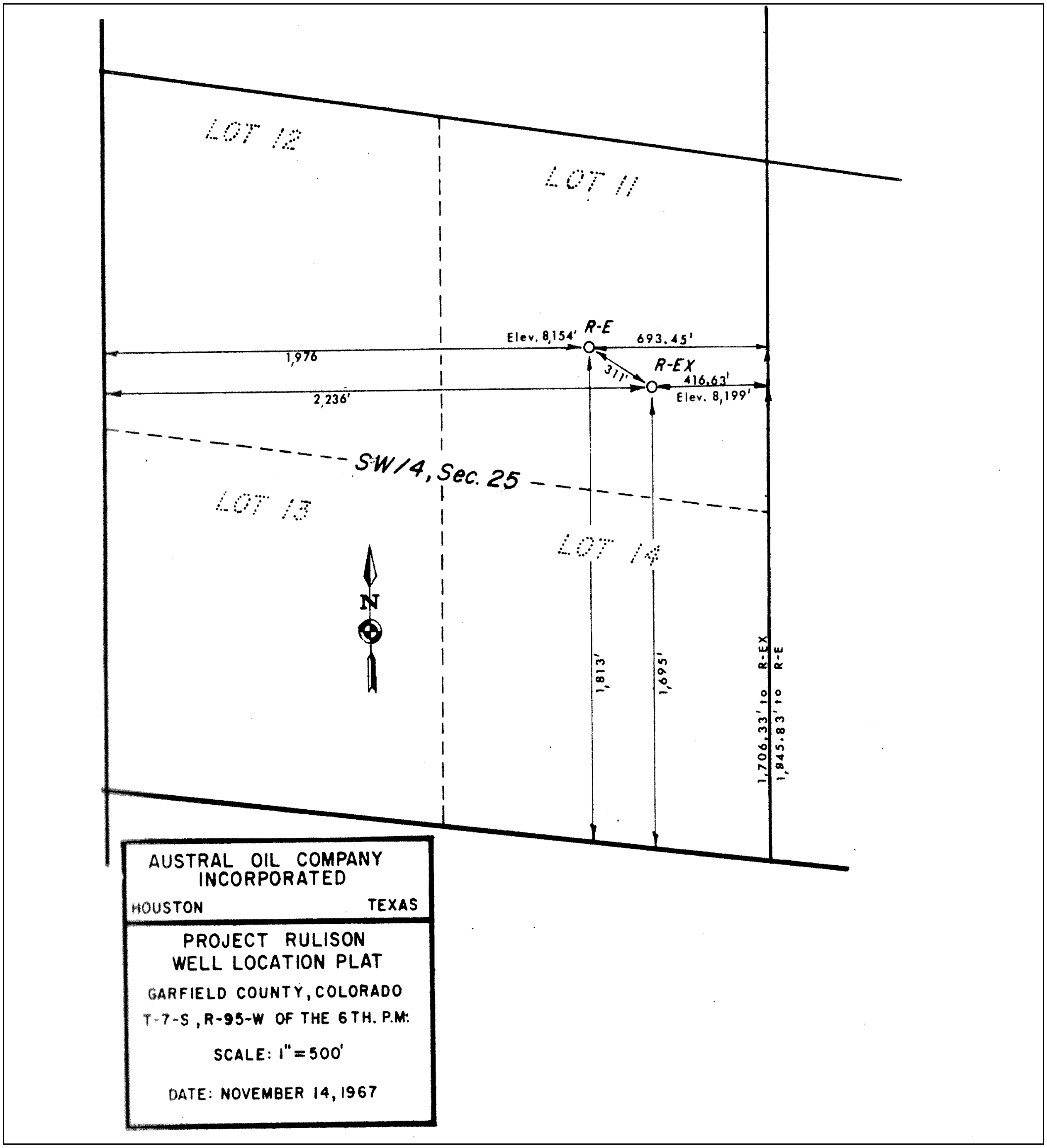


Figure 2-1
Location of Wells R-E and R-EX (Austral Oil Co. and CER Geonuclear, 1969)

Vegetation in the upper end of the Battlement Creek Valley at Rulison consists of quaking aspen, Douglas fir, and Engelmann spruce. Above the site on the mesa, aspen occurs in groves and spruce and fir occur in stands, with grassland and browse (oak brush, service berry) between. At lower elevations, the plants transition to piñon and juniper pine, then oak and mountain mahogany, followed by cottonwood and willow, with sagebrush at the lowest elevations.

The site is located on the east fork of Battlement Creek (Figure 2-2), a few hundred feet east of the main Battlement Creek, and separated by a low ridge. Both forks lie in a narrow, V-shaped valley that heads at the edge of Battlement Mesa, about 2.0 miles southeast of SGZ. Approximately 2.5 miles northwest of SGZ, the narrow valley widens onto a gently sloping bench, Morrisania Mesa, which extends almost to the Colorado River. Battlement Creek crosses this bench and enters the Colorado River approximately 5.5 miles northwest of SGZ (AEC, 1969).

2.1.3 Geologic Setting & Occurrence of Groundwater

The Piceance Creek structural basin is a large northwest-trending downwarp underlying northwestern Colorado. The Rulison Site is located on the southwest limb of this basin such that beds penetrated by site boreholes dip gently northeastward. The basin contains about 27,000 ft of sedimentary rocks. Rocks from the Paleozoic Era and from the Triassic and Jurassic Periods are predominantly of marine origin. Of interest to the Rulison project are the units of Cretaceous and younger age. During the Cretaceous, the depositional environment transitioned from marine to predominantly non-marine. The Cretaceous Mancos Formation contains pro-deltaic marine mudstones and underlies the nuclear test horizon (Figure 2-3). The Rulison test was conducted in the Upper Cretaceous Mesaverde Group, which is approximately 2,500 ft thick at the site. The Mesaverde is divided into the marine regressive deposits of the Iles Formation and the overlying, much thicker, non-marine Williams Fork Formation (the designation of the Williams Fork Formation occurred after the Rulison test so that only the Mesaverde Group is referenced in site literature). The Williams Fork Formation consists of sandstone, shale, and coal deposited during the eastward advance of a large deltaic and coastal plain complex into a retreating sea. Sandstone occurs in discontinuous lenses, many of which only extend for distances of a few thousand feet, interbedded with shale.

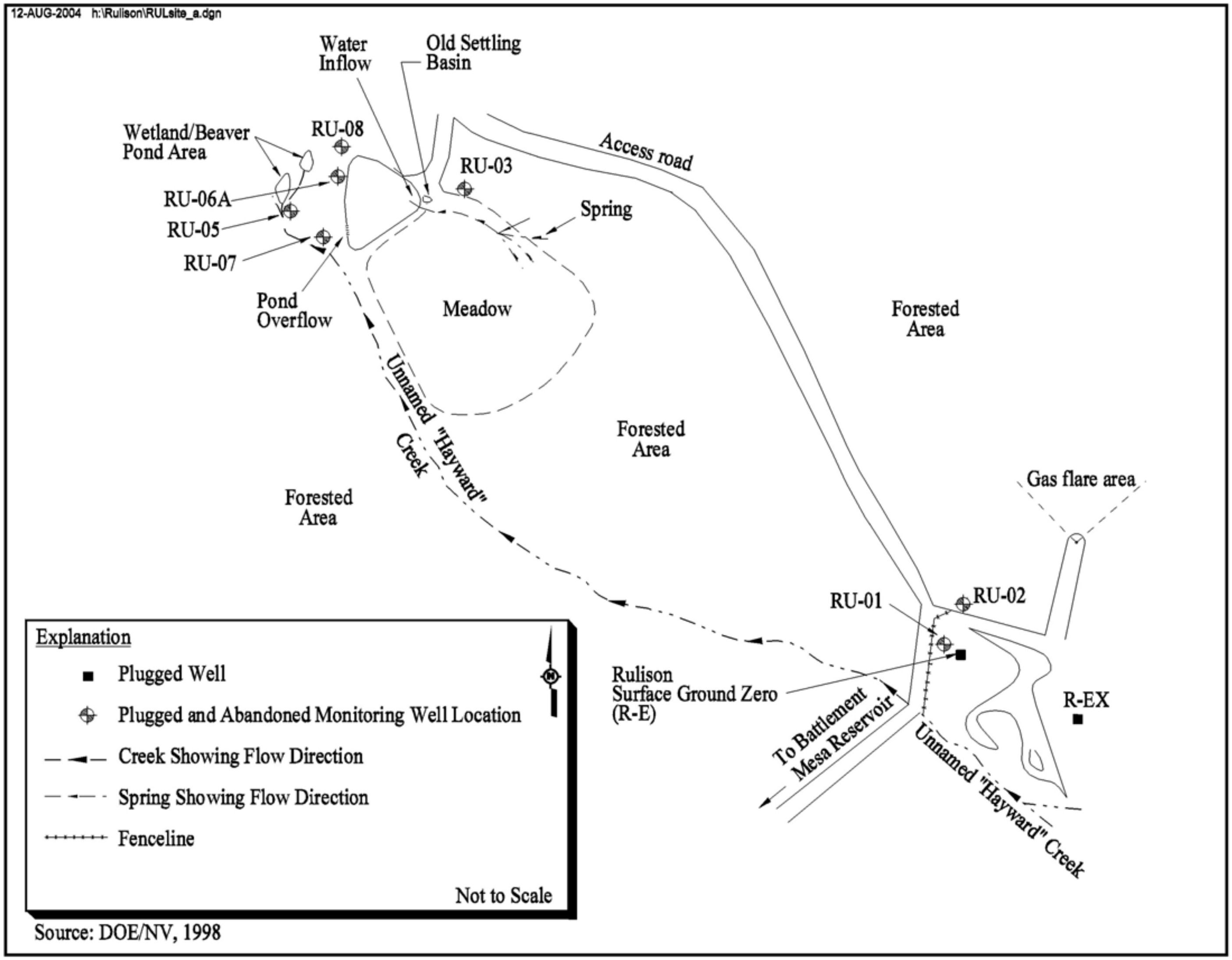


Figure 2-2
Rulison Site Surface Features

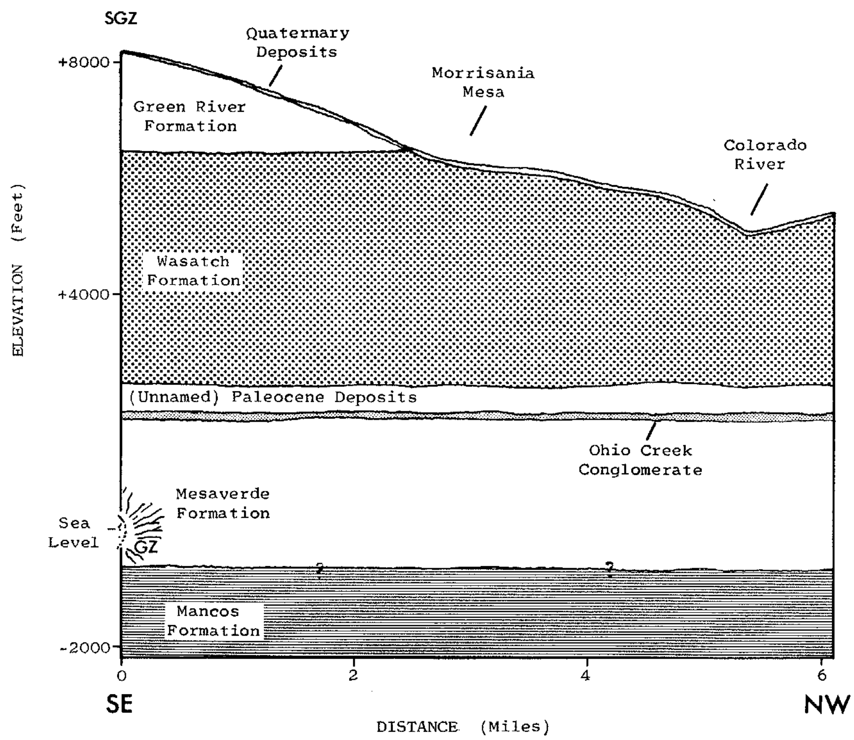


Figure 2-3
Diagrammatic Cross Section of the Rulison Site Along the Trend of Battlement Creek, Showing Ground Zero (GZ) (Nork and Fenske, 1970)

Above the Mesaverde Group is the Ohio Creek Conglomerate. This formation is thin in the Rulison area (37 to 76 ft thick [USGS, 1970]) and is comprised of conglomerates, sandstones, and siltstones. An approximately 500 ft thick unnamed Paleocene-age formation lies above the Ohio Creek Conglomerate and below the Wasatch Formation. This unnamed unit may correlate with the Fort Union Formation elsewhere in the basin. The Wasatch Formation (3,900 ft thick at Rulison) contains claystone, shale, and sandstone, with local occurrences of conglomerate, limestone, coal, and carbonaceous shale. Overlying the Wasatch is the Eocene-age Green River Formation. This formation is about 1,700 ft thick at Rulison and is comprised of shale and marlstone, with minor amounts of sandstone, siltstone, and limestone. The Green River Formation is the primary formation of interest for oil shale development in the region. Quaternary-age deposits of alluvium, mudflows, talus accumulations, and fan and pediment gravels top the geologic section.

Groundwater resources in the Rulison area are confined primarily to surficial deposits (alluvium and fluvial deposits), with the underlying bedrock formations having low permeability and yielding little to no water (Voegeli et al., 1970). Thus, aquifers in the Rulison area are generally limited to alluvium and terrace deposits (Reynolds et al., 1970). Nork and Fenske (1970) suggest that water in the Mesaverde may be immobile. An inventory of wells and springs at the time of the Rulison test indicated only one well in the surrounding area that produced water from bedrock. This well is reported to be 765 ft deep, and is completed in the Green River Formation (Voegeli et al., 1970).

2.2 Site History

Project Rulison was conducted under the Plowshare Program to evaluate the feasibility of using a nuclear device to stimulate natural gas production in low-permeability gas-producing geologic formations. On September 10, 1969, a 40-kiloton nuclear device was detonated at a depth of 8,426 ft below ground surface (bgs) in the R-E test hole (DOE/NV, 2000b; AEC, date unknown). After the test, the R-EX pre-test exploration hole, located 300 ft southeast of the test hole, was redrilled to test gas production in the stimulation zone. Testing in Well R-EX indicated that no water was produced from any formation, though the investigation primarily focused on depths below 5,997 ft (Voegeli, 1969; Reynolds et al., 1970). Natural gas production testing was conducted in 1970 and 1971. Four separate production tests were conducted and 455 million cubic feet (ft^3) of gas were produced. In 1971, the production test well was shut in. The R-E and R-EX drill holes were plugged and abandoned in 1976. Detailed descriptions of the site deactivation and abandonment activities are presented in the *Rulison Site Cleanup Report* (AEC, 1973) and the *Project Rulison Well Plugging and Site Abandonment Final Report* (ERDA, 1977).

2.3 Previous Investigations

Previous work involving surface features of the site is described in the previous section. Subsurface investigations at the site preceded the nuclear test and included investigations of the region's geology and hydrogeology (Voegeli et al., 1970; Voegeli, 1969) and studies of gas production characteristics (AEC, 1969; Austral Oil Co. & CER Geonuclear, 1969). After the Rulison test, there were assessments of the test performance (Reynolds Jr., 1971; Rubin et al., 1972; Alcock et al., 1974; Stosur, 1977), environmental monitoring reports (Johnson et al., 1971; AEC, 1972; DOE/NV, 1984), studies of site conditions preceding closure (AEC, date unknown), and descriptions of site cleanup activities (AEC, 1973; ERDA, 1977). Two assessments of groundwater impacts from the test have been done (Nork and Fenske, 1970; Earman et al., 1996).

With an increase in both local population and gas-well drilling activity, public concern about new drilling encountering Rulison-related radioactivity has increased. In response to this concern, the Colorado Oil and Gas Conservation Commission (COGCC) evaluated the drilling restriction around the site and found it sufficiently protective (Macke, 1998). As an additional caution, the COGCC provides notification to the DOE whenever a natural gas well is permitted within a three-mile radius of Project Rulison so that DOE can determine if the well should be sampled for radionuclides. The DOE sampled natural gas from five production wells in the vicinity of the Rulison test in 1997. Three of the wells were within three miles of SGZ, and two were more than six miles away and served as background. The samples were analyzed for tritium, carbon-14, and krypton-85. No radioactivity was detected in any of the samples (see Appendix A).

3.0 DATA QUALITY OBJECTIVES

The DQO process is a strategic planning approach based on the scientific method that is used to prepare for a site characterization activity. DQOs are used in this plan to develop an effective scientific and resource-efficient investigation design (EPA, 1994). The DQOs for the Rulison subsurface investigation are designed to collect sufficient data and analyses to confirm that the site subsurface was adequately decommissioned, ensuring protection of human health and the environment. The DQO process for the Rulison subsurface is summarized in Table 3-1.

3.1 Conceptual Model of Subsurface Flow and Transport

A conceptual site model illustrates the relationships between the identified potential sources of contamination, the mechanism(s) for release and migration away from the potential source, the pathway(s) the contamination would follow once released, the exposure routes that could affect potential receptors, and the receptors that would be impacted by potential contamination. Figure 3-1 is a flow chart summarizing the conceptual site model for the Rulison Site subsurface.

The Rulison explosive was detonated at a depth of 8,426 ft bgs (AEC, date unknown). The test was completely contained, meaning that no radioactivity was detected at the surface. The detonation vaporized the immediately adjacent rock, forming a cavity with an estimated radius of 76 ft (Rubin et al., 1972) (Figure 3-2). Subsequent collapse of overlying material into the cavity void then created an overlying chimney of large blocks of rock. The Rulison chimney was estimated to be 300 to 350 ft high (ERDA, date unknown). As desired for reservoir stimulation, the nuclear test fractured the adjacent rock. The effective fracture radius was predicted to be.

Table 3-1
Summary of Rulison Subsurface Data Quality Objectives

Subsurface					
Step 1 State the Problem	Is contaminant transport from the test cavity occurring into resources of any value?	Could transport occur from the subsurface source during future resource development?	Does migration pose a potential risk to human health and the environment?		
Step 2 Identify the Decision	**Step 3** Identify the Inputs to the Decision	**Step 4** Define the Study Boundaries	**Step 5** Develop a Decision Rule	**Step 6** Specify Limits on Decision Errors	**Step 7** Optimize the Design for Obtaining Data
Determine the potential radiological constituents and contaminants of potential concern	Historical data Process knowledge Radiological constituents	Modeling boundary to be based on scoping calculations	If calculations predict possible contaminant transport beyond existing drilling restriction boundary, either reduce uncertainty with additional data collection or extend institution controls if indicated by risk assessment	Decision errors are based on model If data is insufficient to make a decision, then additional data will be collected	Develop work plan and technical approach for modeling effort
Determine preliminary action levels for contaminants of potential concern	State and Federal Regulations				
Determine nature and extent of contamination in groundwater, if any	Process knowledge Site data - existing calculations and analyses				
Determine the nature and extent of contamination in the subsurface/natural gas system	Multiphase numerical modeling - possibly sample natural gas wells (determine sampling radius, background concentrations, available wells)				
Determine data needs for risk-based corrective action evaluation	Need for Corrective Action based on Risk Assessment				
Determine risk-based requirements and future land-use scenarios	Groundwater, Natural Gas Resources Area - determine wellhead protection				

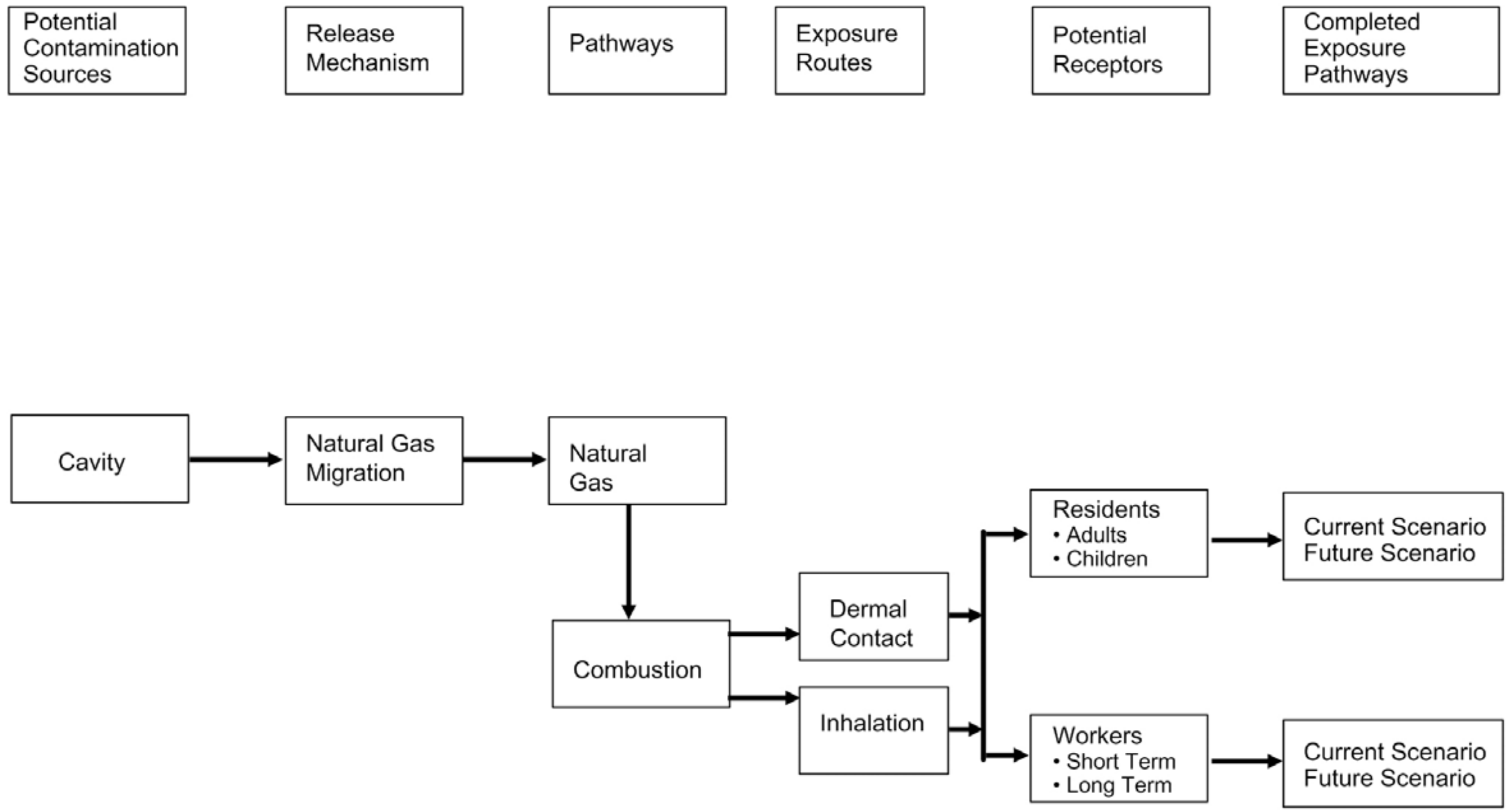


Figure 3-1
Conceptual Site Model for the Rulison Site Subsurface

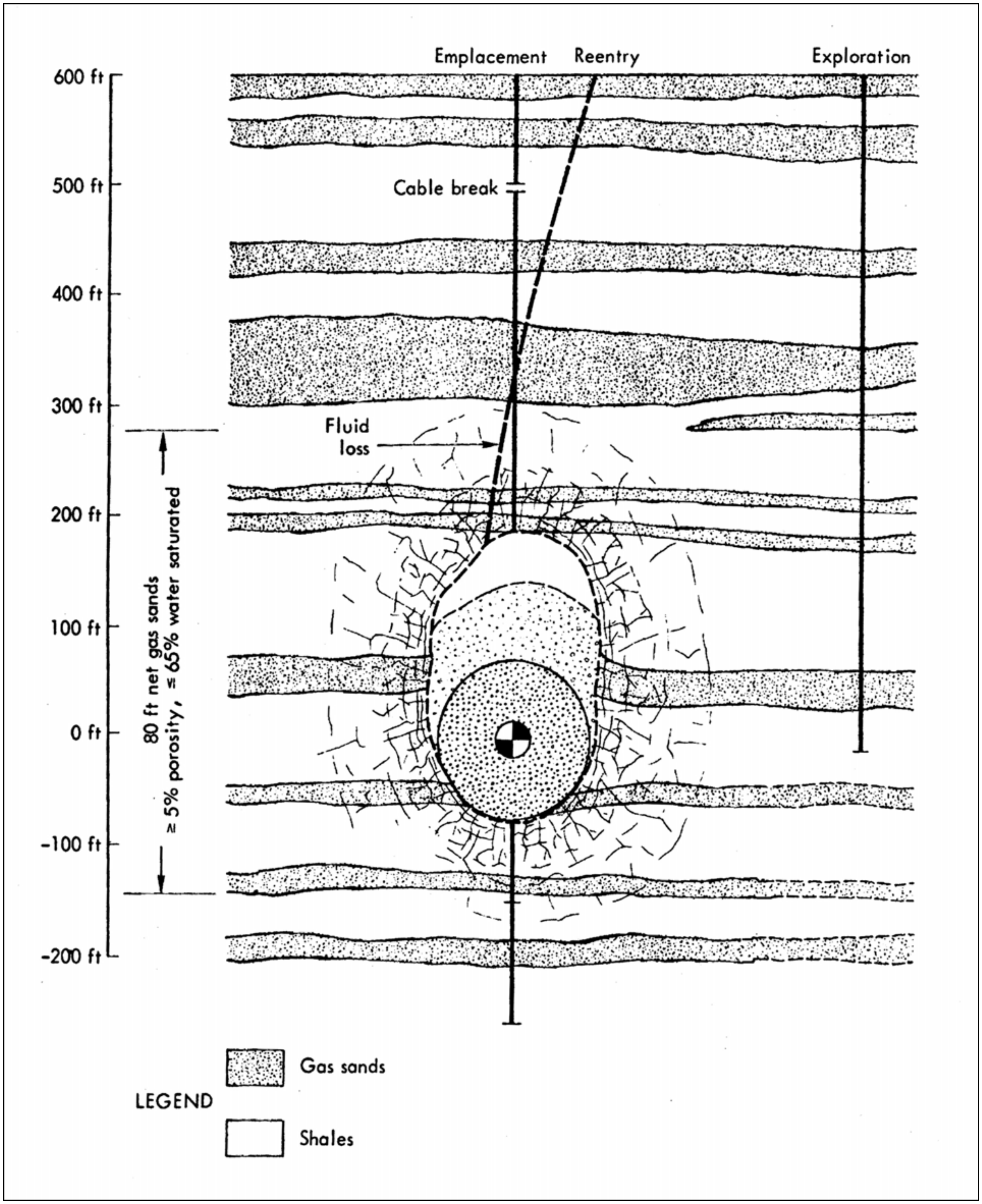


Figure 3-2
Post-Test Cross Section of the Rulison Test (Rubin et al., 1972)

370±70 ft (AEC, 1969), with the depth to major fractures found to be 8,151 ft in the re-entry hole (ERDA, date unknown). Thus, approximately 8,000 ft lie between the nuclear materials and land surface.

Both the emplacement and re-entry wells (R-E and R-EX) were plugged and abandoned in a manner to isolate and confine gas and water to their original reservoirs and prevent migration from one formation to another (Figures 3-3 and 3-4). The plugging was conducted in accordance with criteria in the Rules and Regulations of the COGCC and the Colorado Water Quality Control Commission (ERDA, 1977).

Given the conditions described above, the mechanism for migration from the cavity and chimney source location is either gas or liquid phase movement through subsurface materials. The U.S. Geological Survey (USGS) identifies Quaternary-age deposits as providing the only groundwater resources in the Rulison area. They report the underlying bedrock formations as generally impermeable and yielding little or no water (Voegeli, 1969). Average reservoir properties for the Mesaverde Group in the Rulison Field are a permeability of 0.5 millidarcy (md) and a water saturation of 45 percent. In the exploratory hole specifically, the permeability was 0.11 md (AEC, 1969), and the water saturation was less than or equal to 65 percent (Rubin et al., 1972). Post-test production data and reservoir simulation studies indicated that the actual matrix permeability was approximately 0.001 to 0.04 md (Stosur, 1977). All zones in Well R-EX below 6,000 ft that yielded any water during drilling, or zones interpreted from geophysical logs as likely to contain water, were tested by the USGS. There was little or no fluid entry to the hole for the six intervals tested. The testing concluded that there is little mobile water in the zones (Voegeli, 1969).

The information summarized above and data in the supporting documents are considered sufficient to determine the absence of risk from a groundwater pathway at the Rulison Site. The remaining pathway is that of gas and liquid water migration through the reservoir, and in particular, migration induced by gas production in future wells in the area. Exposure routes to humans from contaminants in the deep subsurface could be through dermal and inhalation routes if natural gas from within the contaminated zone were used as a commercial or residential resource

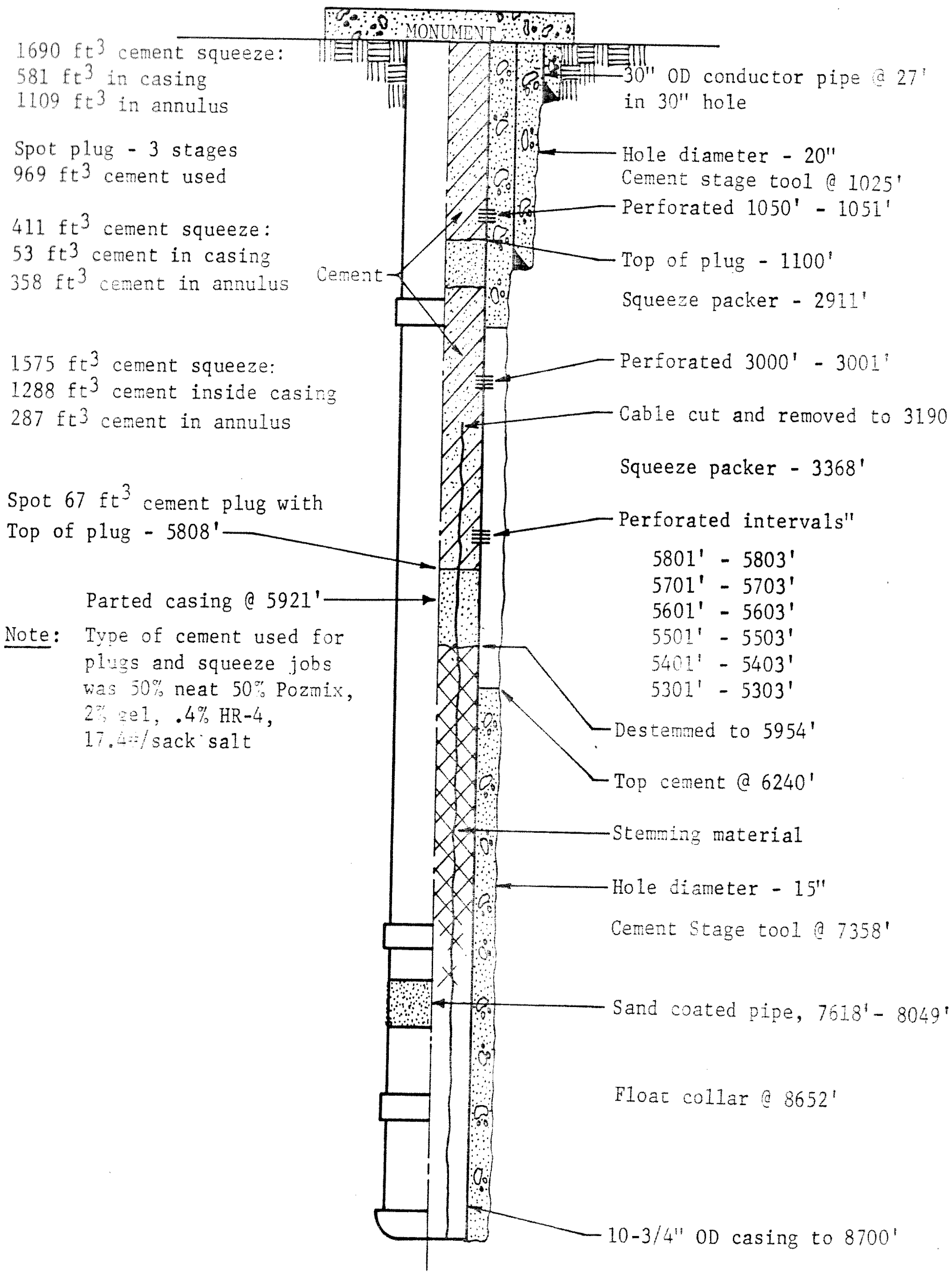


Figure 3-3
As-Built Plugging Condition of Emplacement Well R-E (ERDA, 1977)

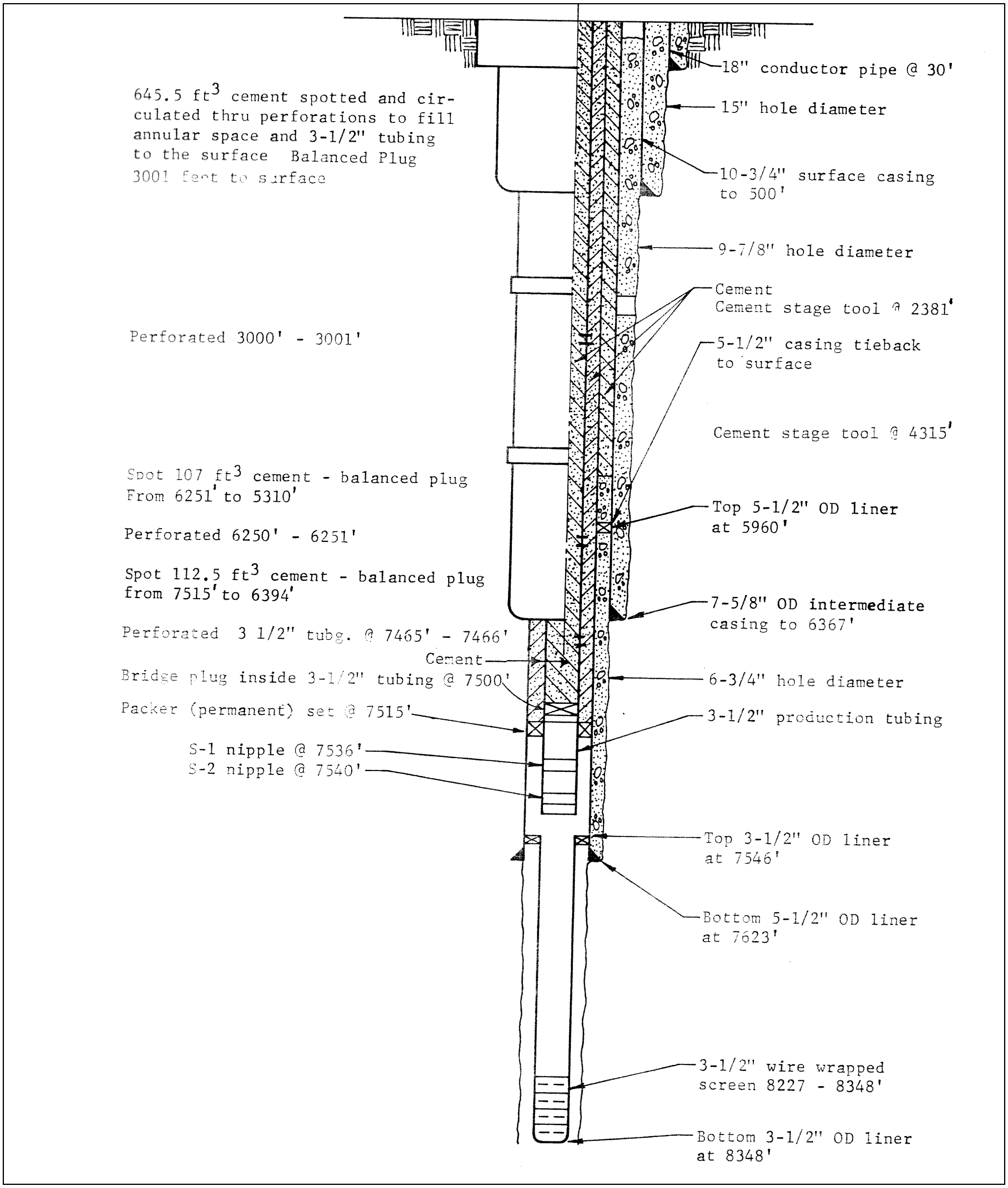


Figure 3-4
As-Built Plugging Condition of Re-Entry Well R-EX (ERDA, 1977)

3.2 Constituents of Potential Concern

The constituents of concern for the migration pathway are gaseous radionuclides. Data from both the Rulison test and the Gasbuggy test (another nuclear gas stimulation test) identified tritium, krypton-85, and carbon-14 as the only radionuclides of significance in the gas for radiation exposure to potential consumers of stimulated gas (Rubin et al., 1972). Other gaseous radionuclides are produced by the test, but have such short half-lives that they rapidly decay to levels below concern. All of the krypton-85 is in the gas phase. Tritium is primarily distributed among water, gaseous hydrocarbons, and pure gas phase, while carbon-14 is primarily distributed among carbon dioxide and gaseous hydrocarbons. Carbon-14 is produced in such small quantities that its contribution to the potential dose to man is very small compared with that of tritium (Rubin et al., 1972). The initial radioactivity estimates for the contaminants of concern at the Rulison Site are listed in Table 3-2.

Table 3-2
Rulison Site Radioactivity Estimates at the Time of the Test

Isotope	Half-life (year)	Nork and Fenske (1970)	Reynolds (1971)	Smith (1971)*
^{3}H	12.3	1,000 to 10,000 curies	10,000 curies	1,310±20 curies
^{14}C	5,730	0.01 to 0.1curies		2.2±0.2 curies
^{85}Kr	10.8	960 curies	1,113 curies	1,100 curies
*totals of gaseous species only				

Significant contaminant mass was removed from the nuclear cavity during production testing and flaring. Records of radionuclide releases during flaring account for 1,064 curies of krypton-85 (AEC, 1972; Colorado Dept. of Health, 1980), suggesting that virtually all of it was removed from the subsurface. Reynolds (1971) asserts that essentially all of the gaseous tritium was removed from the cavity by the end of testing, but notes that this is only about 28 percent of the expected total (2,824 curies were produced), with the remainder being in the liquid phase or trapped in the nuclear melt glass. Stosur (1977) estimated for a generic gas-stimulation test that 5 percent of the total tritium would be in the gaseous phase, 40 percent in melted rock, and about 55 percent in water. A decrease in carbon-14 content of produced carbon dioxide during testing suggested that, in addition to being created by detonation of the nuclear device, carbon dioxide was generated by the heating of the rock after the detonation (which was free of carbon-14).

3.3 Data Quality Objectives of Subsurface Modeling

The objective of the subsurface modeling for Rulison is to determine if there could be contaminant transport from the Rulison test cavity into resources of value, either under existing conditions or during future resource development. If such transport is indicated, it will be determined if the migration poses a potential risk to human health or the environment. This information will be used to identify an appropriate corrective action. Process knowledge, existing data, and analyses are sufficient to determine the absence of risk to any aquifers (Voegeli, 1969; Nork and Fenske, 1970; Earman et al., 1996). Figure 3-5 is a decision flow chart for the subsurface modeling.

The specific issues to address are as follows:

- Determine the nature and extent of contamination in the subsurface and how it changes with time
- Develop likely scenarios for future resource development and determine their possible impact on the extent of contamination
- Evaluate the modeled contaminant extent relative to the existing drilling restrictions

The adequacy of the current drilling exclusion boundary relative to migration of gaseous radionuclides from the Rulison nuclear cavity will be evaluated using mathematical models of flow and transport through geologic media, based on formation property data from the region. The approach will be to simulate the current subsurface conditions in the horizon of the cavity, and then apply hypothetical gas production stress to the formation using reasonable scenarios based on field development history in the region. The results will then be used to evaluate the adequacy of the drilling exclusion boundary. Uncertainty will be incorporated in the analysis, both in terms of uncertainty in parameter values and uncertainty in the postulated production stress. It is anticipated that the inclusion of uncertainty will result in contaminant migration boundaries that are linked to confidence intervals (i.e., a given boundary at the 50 percent confidence interval, or a larger boundary at the 95 percent confidence interval).

There are five decision points identified for the subsurface modeling, with corresponding associated actions:

1. If the data and numerical codes are available to meet the objectives discussed above, then use existing codes; otherwise, develop a new approach.

2. If gas production habits can be characterized with confidence, then use this information in the model; otherwise, reasonable gas production scenarios will be developed in consultation with the COGCC.

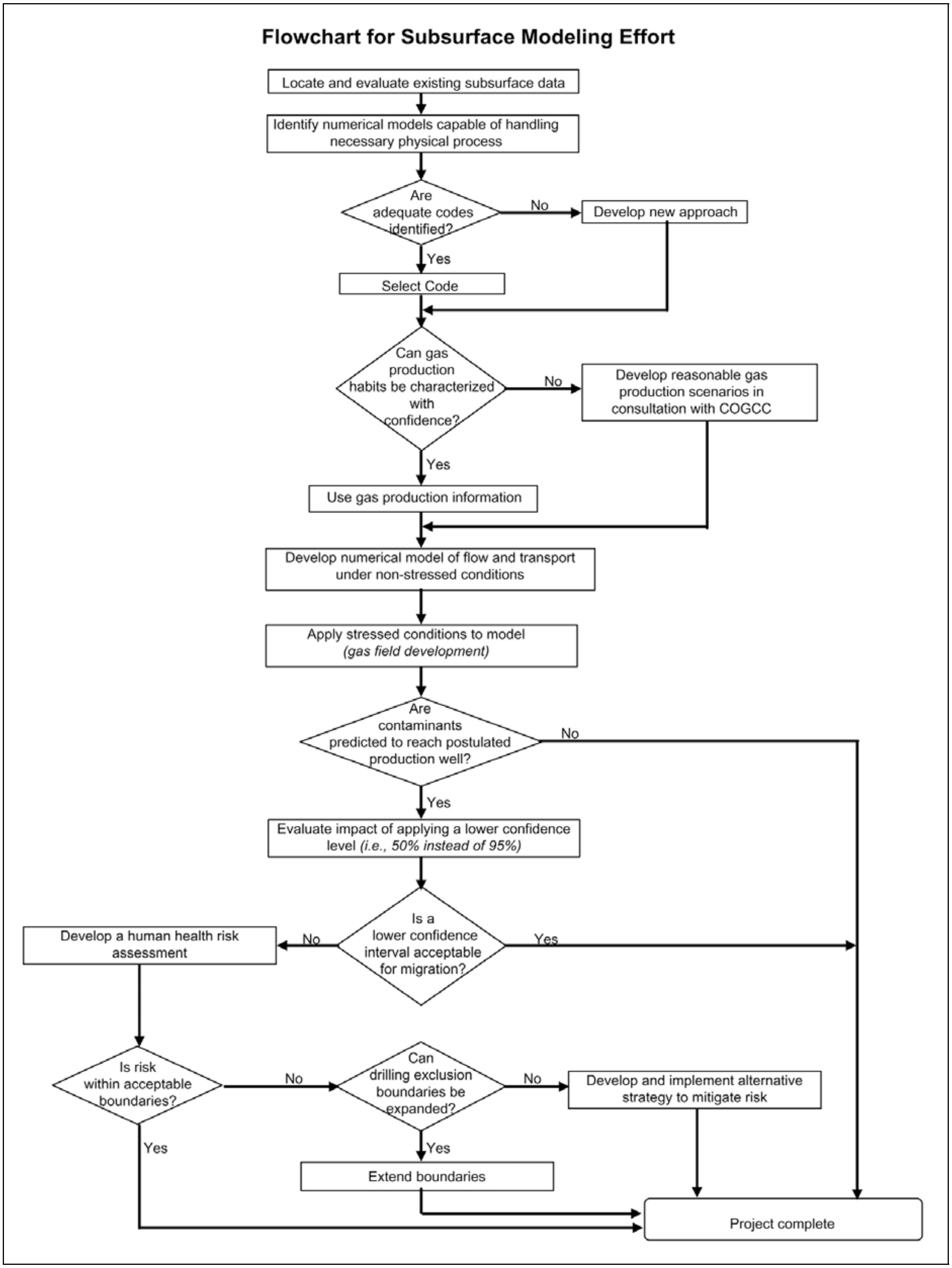


Figure 3-5
Flowchart for Subsurface Modeling Effort

3. Determine if contaminant migration is predicted to postulated production wells. If contamination does not reach production wells, then evaluate the existing boundary relative to the modeling, and the process is complete. If contaminant migration does reach production wells, the impact of applying a lower confidence level (i.e., 50 percent rather than 95 percent) will be evaluated.

4. Decide if a lower confidence interval is acceptable for the migration prediction. If so, the process is complete. If the confidence interval cannot be lowered, then a human health risk assessment will be conducted to determine the significance of possible migration to production wells.

5. Determine if an unacceptable risk is predicted by the results of a human health risk assessment. If risk is acceptable, the process is done. If the risk is unacceptable, the drilling exclusion boundary will be reevaluated and possibly extended.

The modeling process is described in more detail in Section 4.

4.0 MODELING WORK PLAN

The following section discusses the modeling work plan for the Rulison Site.

4.1 Conceptual Model of Subsurface Flow and Transport

Pores in the Mesaverde Group are filled with both gas (approximately 55 percent saturation) and water (approximately 45 percent saturation). Oil, if present, is disregarded as an active phase. In models of two-phase flow through fractured rock, it is commonly assumed that the fracture spacing is larger than the pore space. This results in fractures that contain only a mobile gas phase, while the porous medium contains both gas and liquid (water) phases (Wang and Narasimhan, 1985). This distribution of phases in the rock is derived from considerations of capillarity from the Laplace-Young equation. Both phases are assumed to be continuous throughout the reservoir; they flow in response to pressure gradients of each phase.

Since tritium is an isotope of hydrogen, it is able to form radioactive water molecules. These molecules exist in both the liquid and gas phase, and are capable of being exchanged between phases in time. Detonation of the device created a concentration gradient of tritium. In addition to the pressure-driven flow, radionuclides are transported in both phases by diffusion and dispersion in the porous medium and fractures. The fracture permeability is higher than the permeability of the porous medium, such that the most rapid transport mechanism is flow of tritiated gas through fractures. However, two retardation mechanisms exist that may significantly reduce the distance and rate of transport. The most significant is that diffusion of tritium gas from the fractures to the matrix would reduce the concentration of tritium in the fractures. The second is that tritium is radioactive, with a half-life of 12.26 years. Its daughter product is nonradioactive helium. The degree to which these retardation mechanisms affect transport will be clear when the interplay among the flow rate through fractures, matrix diffusion of tritium gas, and radioactive decay are understood. In addition to tritium, transport of krypton-85 and carbon-14 will also be investigated.

The flow field is probably in a transient state, as production of gas in nearby wells continually acts to decrease reservoir pressure. The Mesaverde Group is bounded below by low-permeability mudstones of the Mancos Formation. Above the Mesaverde are additional thick low-permeability units (the Wasatch and Green River). Initial simulations will focus on axisymmetric flow from a single borehole with a prescribed pressure. The outer boundary condition is no flow at some prescribed distance. It is expected that nonisothermal effects are minimal, though this will be tested in sensitivity studies.

4.2 Evaluation of Existing Subsurface Data

The first task is to refine the initial subsurface flow and transport conceptual model and identify any reasonable alternate models. Literature pertaining to the Piceance Basin will be thoroughly reviewed, and both recent and historic data will be gathered from published sources, oil and gas companies, and regulatory agencies. These data are essential to proper development of the conceptual model and boundary conditions. They will be evaluated to determine mean values and ranges for geologic and hydrologic parameters. These data are to be derived from reservoir tests, borehole logging, and laboratory tests of cores. If data important to development of a successful model are unavailable, data from analogous environments will be used. For example, if estimates of fracture permeability are nonexistent, permeability data from the DOE's Massive Hydraulic Fracturing, Multiwell Experiment, and Slant Hole Completion Tests may be used (Lorenz, 1990; Lorenz and Finley, 1991). New data may also be generated from laboratory experiments if needed. The last step in data collection will be to investigate the history of gas production in the field.

When the available data are understood, an appropriate computer program (simulator) will be chosen to implement the model. The simulator must incorporate the important physical processes (discussed below) with the acquired data.

Some problems are anticipated due to the lack of data for certain crucial processes. One likely problem is that the knowledge of distribution of fracture permeability within the Mesaverde Group may be highly uncertain, although fracture permeability controls gas flow in subsurface media. Another possible issue is that the moisture retention curves of fractures are probably unknown, so that understanding of the pressure-saturation relationship in fractures will be limited. This may also result in inadequate understanding of the relative permeability of fractures under various saturations. Parker et al. (1987) has developed equations for relative permeability between gas and water for porous media, but the parameters for successful simulation of two-phase flow through fractures are unknown. In the event that porous media flow is found to be significant in the conceptual model (in which case, fracture flow and matrix diffusion processes will be relatively unimportant), retention curves for the rock at the test horizon will be needed. Liquid water potential as a function of phase saturation may be determined on cores using a Decagon Dewpoint Potential Meter. A small sample of rock (approximately 10 grams) is saturated in de-aired water, and its potential is measured in the dewpoint potential and recorded. The sample is then allowed to dry for several days, and the process is repeated until potential values covering the expected potentials in the reservoir are measured. A plot of water potential versus water content is made, and the data are fit to a model (usually the Brooks and Corey model [Corey, 1994]).

Another anticipated problem is that it will be difficult to estimate retardation of radionuclides due to fracture-matrix interaction (matrix diffusion). Matrix diffusion is the diffusion of gases from a fracture to the adjacent matrix. Since most of the gas flow may be through fractures, a chemical gradient may exist for those species containing radionuclides that are migrating from the fracture to the matrix; as a result, the matrix may act as a sink for radionuclides and retard their transport. To correctly implement matrix diffusion into the model, a gas phase diffusion coefficient is required for each radionuclide. The diffusion coefficient for gases is a product of the free air diffusion coefficient (available in handbooks) and the tortuosity of the rock matrix. Tortuosity can be calculated from core samples using a diffusion cell apparatus and the solutions developed by Moridis (1999). A set of experiments can be conducted whereby gas containing a tracer is passed through a rock sample and the tracer concentration is measured at the outflow end of the sample. The tracer concentration is plotted, and the (usually) lognormal data are fit to a curve. The diffusion coefficient for the rock is determined, and the tortuosity is determined by dividing the rock's diffusion coefficient value by the free air diffusion coefficient.

4.3 Identification of Proper Numerical Simulator

Flow and transport in this complex subsurface environment are coupled processes that must be solved simultaneously in order to get a realistic understanding of the radionuclide distribution.

Nearly all petroleum-oriented simulators solve for the flow field only. In contrast, most contaminant-oriented simulators do not solve for gas as an active phase. Few choices exist for the proper simulation of this subsurface environment.

The processes that need to be simulated include transient three-dimensional multiphase, multicomponent flow in Cartesian coordinates; active gas and liquid phase flow; radionuclide transport and decay; sources and sinks of mass; and phase change of water. Although we believe temperature dependence to be negligible at this time, it may be determined later that a nonisothermal flow code is needed. The code must be flexible enough to allow for writing specific pressure-saturation functions, implementing both fracture and matrix flow, matrix diffusion, and changing of the equations of state for gas and water, if need be. The program must not be proprietary, so that changes can be made to the source code.

Two programs exist that may meet the criteria. The Transport of Unsaturated Groundwater Heat (TOUGH2) simulator (Pruess, 1991) is a DOE-sponsored code that has been used extensively to study heat and mass flow in geothermal reservoirs, saturated/unsaturated zones, and oil and gas reservoirs. It has been used in studies of both nuclear waste isolation and environmental remediation (Pruess, 1995; Pruess, 1998). McPherson and Bredehoeft (1995) and McPherson (1996) used the TOUGH2 simulator to study the impact of overpressuring on oil and gas migration in the Uinta Basin. TOUGH2 is currently being used for flow and transport simulations of the Rio Blanco nuclear test site.

The second possible program is the Finite Element Heat and Mass (FEHM) simulator (Zyvoloski et al., 1996), developed at Los Alamos National Laboratory, which models three-dimensional, time-dependent, multiphase, multi-component, non-isothermal reactive flow through porous and fractured media. However, it appears that only an executable version is available; therefore, FEHM may not be flexible enough for use on this project. Given the suitability of TOUGH2 for use at Rio Blanco, it will be used for Rulison as well.

4.4 Modeling Process

The subsurface flow and transport model will focus on flow around the emplacement hole and production holes (Wells R-E and R-EX). Initial simulations will focus on transient radial flow and radionuclide transport around the nuclear cavity. The lateral extent of the model domain will not be determined until the existing data have been analyzed. The complexity of the domain will be increased by adding adjacent hypothetical production wells and by varying reservoir properties as interpreted from the data. The last step will be to hypothesize pumping scenarios in nearby production gas wells and to apply these rates to the model. This will allow us to estimate radionuclide transport in future pumping scenarios. The domain will be extended until "far field" flow and transport effects are diminished. Simulation results will be continually calibrated to pressure and flow data as the model is developed.

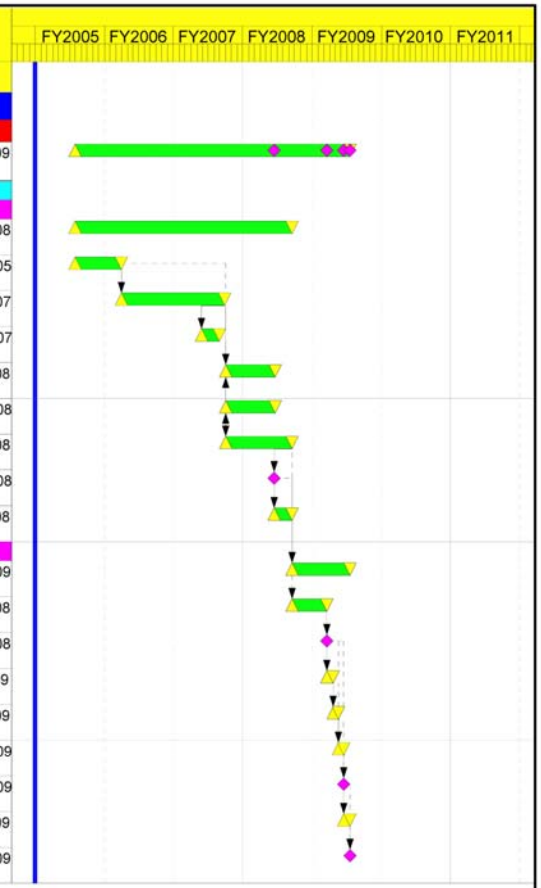
4.5 Evaluation of Results

The results of simulations will be evaluated to determine the extent of potential radionuclide migration from the Rulison cavity. An uncertainty analysis will be conducted so that minimum and maximum radionuclide transport distances and times can be estimated with a corresponding degree of confidence. The current drilling exclusion zone will be evaluated and possibly altered depending on the results from various stressed (pumping) and non-stressed reservoir conditions.

5.0 REPORTING

A tentative project schedule has been developed and is presented in Figure 5-1. This schedule provides information regarding start times and durations for the tasks to be completed as part of the Rulison Site subsurface modeling activity. This schedule also identifies reporting requirements for the Rulison project.

Activity ID	CNTR	CAU	Activity Description	Orig Dur	Early Start	Early Finish
1.4.1.4.02 COLORADO						
1.4.1.4.02.02 RULISON SITE						
1.4.1.4.02.02.03 RULISON SUBSURFACE						
		1023		1,035	02MAY2005	17APR2009
1.4.1.4.02.02.03.22 CORRECTIVE ACTION DECISION DOCUMENT (CADD)						
1.4.1.4.02.02.03.22.04 MODELING / ANALYTICAL						
OSC8085	12	1023	Conduct the Modeling Effort	817	02MAY2005	17JUN2008
OSC9001	12	1023	Data Acquisition	173	02MAY2005	28DEC2005
OSC9015	12	1023	Flow and Transport Analysis	392	29DEC2005	29JUN2007
OSI8090	21	1023	RAD Risk Analysis	66	28FEB2007	30MAY2007
OSC9076	12	1023	Model Validation Plan	189	02JUL2007	20MAR2008
OSC9078	12	1023	Monitoring Strategy	189	02JUL2007	20MAR2008
OSC9077	12	1023	Contaminant Boundary Determination	252	02JUL2007	17JUN2008
OSC9020	12	1023	Submit Modeling Rpt to DOE/Tech Working Group	0		17MAR2008
OSD9021	28	1023	DOE/TWG Review	66	18MAR2008	17JUN2008
1.4.1.4.02.02.03.22.05 PREPARE DOC						
OSI9060	21	1023	Prepare Decision Document	218	18JUN2008	17APR2009
OSI9055X	21	1023	Prepare Draft Document	132*	18JUN2008	18DEC2008
OS28R2D0S	28	1023	Deliver Decision Document to State - (Rev 0)	0		18DEC2008
OSX9100	37	1023	State Review & Comments	22	19DEC2008	19JAN2009
OSI9110	21	1023	Respond to State Comments	20	20JAN2009	16FEB2009
OSD9115	28	1023	DOE & OPAI Review (Rev 1)	22	17FEB2009	18MAR2009
OS28R2D0F	28	1023	Deliver Decision Document to State (Rev 1)	0		18MAR2009
OSX9125	37	1023	State Review (Rev 1)	22	19MAR2009	17APR2009
OS37R2D0X	37	1023	Receive State Approval - Decision Doc (Rev 1)	0		17APR2009



Start Date	01OCT87
Finish Date	06DEC69
Data Date	01OCT04
Run Date	19OCT04 08:37

Early Bar
Progress Bar
Critical Activity

LCBL - OS01

Sheet 1 of 1

U.S. DOE NNSA / NSO
OFFSITES LC BASELINE

Figure 5-1
Rulison Project Schedule for Subsurface Modeling

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Appendix A

Discussion of 1997 Rulison Site Natural Gas Sampling Results

INTERNATIONAL TECHNOLOGY CORPORATION

RECORD OF ■ TELECON ☐ MEETING

Project Name	Number	Phase	Task	Subtask
RULISON	772862			

Date: 6 October 97 Time: 0800 – 0830

CALL FROM ■ CALL TO ☐ NAME: STEVE ADAMS

CALL FROM ☐ CALL TO ■ NAME: PETE SANDERS

Telephone Number: 295- 1037

Company Name: DOE NV ERD

Address: NSF

City:

State: Zip Code:

Other Participants — Name/Location/Representing: NONE

Topic: LLNL GAS ANALYSIS RULISON NATURAL GAS SAMPLES

Summary (Decisions & Specific Actions Required by Named Persons): PETE SANDERS FAXED LLNL ANALYSIS OF RULISON GAS SAMPLES (ATTACHED). PETE REQUESTED THAT I REVIEW DATA & COMPARE TO NATIONAL CLEAN AIR ACT. CALLED PETE BACK TO INFORM HIM THAT: (1) GROSS MEASUREMENT OF ^{14}C + ^{3}H + ^{85}Kr IS NOT POSITIVE, NOT DIFFERENT THAN ZERO. (2) THE MINIMUM DETECTABLE CONCENTRATION IS NOT LOW ENOUGH TO MAKE COMPARISON TO CLEAN AIR ACT 40 CFR ~~PART~~ 61, H (3) SUGGESTED THAT ADDITIONAL ANALYSIS REQUIRED. (5) IF THERE IS NO DILUTION THE CONCENTRATION OF ORGANIC ^{14}C IS $6 \cdot 10^{-10}$ µCi/mL = 0.6 pCi/L. MDA OF ANALYSIS APPROXIMATELY 27- 42 pCi/L. MUST GET ANALYTICAL MDC < 0.6 pCi/L.

ISOTOPE	MINIMUM DETECTION LEVEL @ 95%
^{14}C	0.6 pCi/L
^{3}H	10 pCi/L
^{85}Kr	300 pCi/L

Required Action: CALL TIM WHITE, INFORM HIM OF CONVERSATION WITH PETE SANDERS

Prepared by (Signature):

Distribution:
Original to Project File
Copy to Project Manager
Copy to Preparer

■ Other Distribution (By Preparer)
JEFF WURTZ
MIKE O'HAGAN

PAGE 1 OF 2

548A-6-87

RECEIVED
OCT 0 1 1997
IT/LAS VEGAS

Noble Gas Analysis Laboratory
Isotope Sciences Division, LLNL
9/22/97
Bryant Hudson (510-423-2947) Bryant Hudson

The Isotope Sciences Division received 5 natural gas samples from the U.S. Dept. of Energy, Nevada Operations Office for radiochemical analysis on 8/24/97. Initial screening using thin-window beta counting showed no activity (< 200 dpm/liter). We settled on internal gas proportional counting as an appropriate method for analysis. This counting technique is equally sensitive (approximately) to tritium, ^{14}C and ^{85}Kr (see attached reference, Bonner and Finkel, UCID-21538 for more details). Because the gas samples consist principally of methane, we can use the gas sample directly in the counter without any chemical processing or dilution with other gases. Blanks consisted of methane normally used as the diluting quench gas. Sample fill pressure was approximately 1500 torr. For each fill, the counter performance was checked using an ^{55}Fe x-ray source via a Be-window in the counter. Each sample was analyzed 4 times (except RUG00001 which was analyzed 3 times). The uncertainty is dominated by the background count rates of the individual counting tubes which ranged from 50 to 160 counts per minute. These are relatively high backgrounds for this system. As the counting tubes age, the backgrounds slowly increase as fixed contamination builds up. We periodically disassemble the counting tubes and clean them to lower the background. We have assumed a conservative 50% uncertainty (as 1 standard deviation) in the background correction for an individual analysis. Each sample was analyzed using at least 2 different counting tubes. Final results are the weighted average of the individual analyses and the uncertainty is a 95% confidence interval for the weighted average. Since the analysis does not discriminate between tritium, ^{14}C and ^{85}Kr, the total activity represents the sum of all gaseous radioactive isotopes. For future work (if slightly more advance notice is possible), the detection limits could be reduced considerably (about a factor of ten) by employing recently rebuilt counting tubes.

Sample number	Total activity (pCi/L)	+- (pCi/L, 95% confidence)
RUG00001	7	42
RUG00002	-1	27
RUG00003	1	27
RUG00004	-7	27
RUG00005	15	27